

# Possible Resolutions of the $D$ -Paradox

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(Dated: February 7, 2008)

We propose possible ways of explaining the net charge event-by-event fluctuations in Au+Au collisions at the Relativistic Heavy Ion Collider within a quark recombination model. We discuss various methods of estimating the number of quarks at recombination and their implications for the predicted net charge fluctuations. We also discuss the possibility of diquark and quark-antiquark clustering above the deconfinement temperature.

Fluctuations of the net electric charge of all particles emitted into a specified rapidity window have been proposed as a possible signal for the formation of deconfined quark matter in relativistic heavy ion collisions [1, 2]. The argument at the basis of this proposal is that charge fluctuations in a quark-gluon plasma are expected to be significantly smaller (by a factor 3–4) than in a hadronic gas. Because the net charge contained in a given volume is locally conserved and can only be changed by particle diffusion, thermal fluctuations generated within the deconfined phase could survive hadronization and final state interactions. Quantitative estimates of the diffusion of net charge showed that the survival of these fluctuations from an early stage of the collision requires a moderately large rapidity window [3].

The most widely used measure for the entropy normalized net charge fluctuations is the  $D$  measure [2]:

$$D = 4\langle(\Delta Q)^2\rangle/N_{\text{ch}}, \quad (1)$$

where  $\langle(\Delta Q)^2\rangle$  denotes the event-by-event net charge fluctuation within a given rapidity window  $\Delta y$ , and  $N_{\text{ch}}$  is the total number of charged particles emitted in this window. For a free plasma of quarks and gluons  $D \approx 1$ , while for a free pion gas  $D \approx 4$ . For the comparison with experimental data a number of corrections for acceptance and global charge conservation must be applied to the expression for  $D$  [4]. The relation of the  $D$ -measure to other measures of net charge fluctuations has been discussed by various authors [5, 6, 7].

Several experiments have measured net charge fluctuations in heavy ion collisions at the CERN Super-Proton Synchrotron (SPS) and at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven [8, 9, 10, 11]. The results for  $D$  are generally somewhat smaller than 4, but much larger than the value predicted for a free quark-gluon gas. For example, the STAR collaboration has measured  $D = 2.8 \pm 0.05$  in central Au+Au collisions at  $\sqrt{s_{NN}} = 130$  GeV [8], before applying corrections for global charge conservation and other effects [4]. The PHENIX experiment measured net charge fluctuations in a limited azimuthal acceptance window around midrapidity, which extrapolate to a value  $D \approx 3$  [9]. These results are surprising, because many other observables indicate that a

deconfined quark-gluon plasma is formed in these collisions.

Białas has argued that the measured values of  $D$  could be compatible with the net charge fluctuations in a deconfined quark phase, if hadronization proceeds according to simple valence quark counting rules [12] and if gluons do not play an active role in the hadronization. Indeed, hadron abundances measured in relativistic heavy ion collisions at the SPS and RHIC are well described by combinatorial quark recombination models, such as ALCOR [13]. We here pursue this idea further and explore various scenarios of valence quark recombination in order to better understand how the puzzle posed by the measured value of  $D$  can be resolved. We also discuss the constraints on such a resolution from the measured final-state entropy and the second law of thermodynamics.

The recombination of thermalized valence quarks has recently been proposed as the dominant mechanism for the production of hadrons with transverse momenta of a few GeV/c in Au+Au collisions at RHIC [14, 15, 16, 17, 18, 19]. The RHIC data have provided compelling evidence for this hadronization mechanism [20, 21]. Valence quark recombination explains the enhancement of baryon emission, compared with meson emission, in the range of intermediate transverse momenta (roughly from 2 to 5 GeV/c), and it naturally describes the observed hadron species dependence of the elliptic flow in the same momentum region in terms of a universal elliptic flow curve for the constituent quarks [15].

When one wants to describe hadronization by quark recombination not only at intermediate momenta, but over the entire hadron momentum range, except for very large momenta where parton fragmentation is thought to dominate, entropy becomes an important consideration. The naive application of recombination can easily entail a violation of the second law of thermodynamics, because the number of independent particles decreases when valence quarks recombine into hadrons. Greco *et al.* [16] have argued that this problem may be circumvented by including the decay of hadronic resonances, such as the  $\rho$ -meson, into the calculation of the entropy balance. We next discuss the entropy problem in a more comprehen-

sive manner by considering the entropy content in realistic models of the hadronic phase (the resonance gas model) and the quark phase (lattice-QCD calculations).

The equilibrium entropy per particle is only a fixed constant (3.60 for bosons, 4.20 for fermions) for free massless particles. For particle with mass, the entropy per particle is a function of the particle mass  $m$  and the temperature  $T$ . For  $m/T > 3$  a good approximation is  $S/N = 3.50 + m/3T$ . The inclusion of mass is important, since a large fraction of the hadrons created at the moment of hadronization is quite heavy – the average hadron mass at chemical freezeout is about 800 MeV/ $c^2$  in the absence of medium induced modifications of the hadron masses. The average value of the entropy per hadron therefore significantly exceeds the canonical value  $(S/N)_0 \approx 4$  in thermal equilibrium. Including only the pseudoscalar and vector ground state meson nonets and the octet and decuplet baryons, one finds  $\langle S/N \rangle = 4.72$  at  $T = T_c = 170$  MeV; including all known meson and baryon resonances, one obtains  $\langle S/N \rangle = 5.15$ .

An estimate of the final-state entropy per unit rapidity produced in central  $\sqrt{s_{NN}} = 130$  GeV Au+Au collisions has recently been derived from experimental data (hadron yields, spectra, and source radii) by Pal and Pratt:  $dS/dy = 4450 \pm 400$  [22]. Using the measured charged multiplicity of  $dN_{ch}/dy = 526 \pm 2(\text{stat}) \pm 36(\text{syst})$  [8], this value can be converted into an estimate of the final entropy per particle of  $S/N \approx (dS/dy)/(1.5dN_{ch}/dy) \approx 5.64 \pm 0.6$ , which is slightly higher, but agrees within error with the equilibrium value for the full resonance gas at chemical freezeout. Indeed, numerical simulations of the reactions among hadrons in the hadron gas phase [23] show that the particle number increases only slightly (by about 5%) due to interactions after hadronization, compared with the number obtained by letting all hadrons formed at chemical freezeout decouple and decay without reinteraction. A modest increase in the value of  $S/N$  during the hadron gas phase can easily be understood as the effect of volume expansion, since the entropy per particle for fixed particle number increases logarithmically with the volume:  $S/N = S_{eq}/N + \ln(V/V_{eq})$ .

At the same time, the entropy content of the quark phase is strongly reduced due to interactions near  $T_c$ . Recently, the CP-PACS collaboration [24] and the Bielefeld group [25] have calculated the pressure and energy density at finite temperature and zero chemical potential on the lattice. The Bielefeld simulation was done keeping the ratio  $m_q/T$  fixed, while the one by the CP-PACS collaboration was performed with the ratio of pseudo-scalar to vector meson masses,  $m_{PS}/m_V$  fixed. The CP-PACS collaboration used temporal lattice sizes  $N_t = 4, 6$  and  $N_f = 2$  quark flavors; the Bielefeld group used only  $N_t = 4$ , but explored a range of flavor multiplicities  $N_f = 2, 2+1$ , and 3. In order to extract physical quantities from lattice QCD calculations, extrapolations (to the

thermodynamic limit, continuum limit, etc.) are mandatory. Because of a finer lattice spacing at a given temperature, the CP-PACS simulation for  $N_t = 6$  is closer to the continuum limit and may be slightly better suited for the purpose of extracting the entropy density near  $T_c$ . We use these results here. However, we should keep in mind that all lattice data for thermodynamic quantities are still obtained with unphysically large quark masses.

We list the obtained values of  $\varepsilon/T^4$ ,  $P/T^4$ ,  $\varepsilon/\varepsilon_{SB}$ ,  $P/P_{SB}$ , and  $s/s_{SB}$ , at  $m_{PS}/m_V = 0.65$  and 0.80 below in Tables I and II.  $\varepsilon$ ,  $P$ , and  $s$  denote the energy density, pressure, and entropy density, respectively, and  $\varepsilon_{SB}$ ,  $P_{SB}$ , and  $s_{SB}$ , are their values for the free gas of massless quarks and gluons on the lattice used in the simulation. The statistical errors are shown only for  $s/s_{SB}$ . Obviously, the size of the systematic errors are still substantial. However, at the same time, it is obvious that the entropy density of the quark-gluon plasma is considerably suppressed with respect to the corresponding Stefan-Boltzmann (SB) value near  $T_c$ .

TABLE I:  $m_{PS}/m_V = 0.65$  case. All calculations are performed with ( $N_t = 6$ ). Statistical errors are shown only for  $s/s_{SB}$ .

$T/T_c$	$\varepsilon/T^4$	$P/T^4$	$\varepsilon/\varepsilon_{SB}$	$P/P_{SB}$	$s/s_{SB}$
0.92	8.03	0.88	0.489	0.172	$0.413 \pm 0.051$
1.04	11.91	1.28	0.725	0.250	$0.612 \pm 0.043$
1.30	13.67	2.75	0.833	0.536	$0.762 \pm 0.038$
1.61	14.44	3.35	0.879	0.653	$0.826 \pm 0.038$
2.00	12.93	3.96	0.787	0.772	$0.784 \pm 0.038$

TABLE II: Same as Table I except  $m_{PS}/m_V = 0.80$ .

$T/T_c$	$\varepsilon/T^4$	$P/T^4$	$\varepsilon/\varepsilon_{SB}$	$P/P_{SB}$	$s/s_{SB}$
0.80	3.73	0.17	0.227	0.033	$0.181 \pm 0.054$
0.89	1.91	0.26	0.116	0.061	$0.101 \pm 0.041$
1.12	12.08	1.62	0.736	0.316	$0.636 \pm 0.044$
1.38	11.98	2.66	0.730	0.519	$0.679 \pm 0.042$
1.67	11.80	3.54	0.719	0.690	$0.712 \pm 0.039$

From these results we conclude the following:

1. The entropy per particle in the hadronic gas, and therefore the entropy content of the hadronic phase at chemical freezeout, is considerably larger than often assumed.
2. The entropy density of the quark phase is significantly suppressed near  $T_c$ , most likely due to correlations among the quasiparticles caused by their strong interactions.

These two conclusions make the recombination picture of hadronization more compatible with the entropy constraint. Namely, if the quark-gluon plasma at hadronization consists of strongly interacting quasi-particles (possibly constituent quarks) with strong correlations, and if many of the hadrons created at hadronization are heavy, quark recombination and the concomitant particle number decrease can be more easily reconciled with the second law of thermodynamics.

As we have seen, the increased entropy per hadron in the massive resonance gas may well allow for an isentropic transition from the deconfined to the confined phase by (sudden) quark recombination. At present, however, we cannot directly compare the entropy content of both phases, since the volume at hadronization is not unambiguously known. Therefore, we cannot convert the entropy density determined on the lattice into a total entropy. Furthermore, lattice calculations do not tell us the number of (quasi-)particles, because there is no lattice definition of particle density. Therefore, a more detailed comparison of the entropy content of the hadronic phase and the quark phase at hadronization remains as a problem for future investigations.

We now return to the calculation of net charge fluctuations in a bulk recombination scenario. The fluctuations of the net charge  $Q = \sum_i q_i n_i$  are given by

$$\begin{aligned} \langle \delta Q^2 \rangle &\equiv \langle Q^2 \rangle - \langle Q \rangle^2 \\ &= \sum_i (q_i)^2 \langle n_i \rangle + \sum_{i,k} c_{ik}^{(2)} \langle n_i \rangle \langle n_k \rangle q_i q_k \end{aligned} \quad (2)$$

where  $c_{ik}^{(2)}$  are the normalized two-particle correlation functions:

$$c_{ii}^{(2)} = \frac{\langle n_i(n_i - 1) \rangle}{\langle n_i \rangle^2} - 1 \quad (i = k); \quad (3)$$

$$\begin{aligned} c_{ik}^{(2)} &= \frac{\langle n_i n_k \rangle}{\langle n_i \rangle \langle n_k \rangle} - 1 \\ &= \frac{\langle (n_i - \langle n_i \rangle)(n_k - \langle n_k \rangle) \rangle}{\langle n_i \rangle \langle n_k \rangle} \quad (i \neq k). \end{aligned} \quad (4)$$

The last expression in eq. (4) shows that  $c_{ik}^{(2)}$  is positive if there is a positive correlation between the quarks of flavors  $i$  and  $k$ . In the absence of two-particle correlations, (2) can be rewritten as:

$$\langle \delta Q^2 \rangle = \frac{4}{9}(N_u + N_{\bar{u}}) + \frac{1}{9}(N_d + N_{\bar{d}} + N_s + N_{\bar{s}}), \quad (5)$$

where  $N_i = \langle n_i \rangle$  denotes the average number of constituent quarks of flavor  $i$ .

Our strategy is now as follows: Knowing the number of final-state charged hadrons within a given rapidity interval,  $dN_{\text{ch}}/dy$ , we can extrapolate by means of the statistical hadronization model [26, 27] to the thermal abundances of hadrons produced at the critical temperature  $T_c$ . We can then determine the total number and

flavor distribution of valence quarks contained in these hadrons. Assuming valence quark recombination, using eq. (5), and neglecting correlations, we can then calculate the expected net charge fluctuation at hadronization. The prediction for  $\langle \delta Q^2 \rangle$  derived in this way can then be compared with the measured value of this quantity.

We start from the measured charged multiplicity in central Au+Au collisions at 130A·GeV mentioned above. Including all established meson and baryon resonances in the chemical freezeout, we find that a total hadron number  $dN_{\text{had}}/dy = 507 \pm 35$  is needed at  $T_c$  to generate this charged particle number, when all sequential decays of unstable hadrons are taken into account. These 507 hadrons contain a total of 1125 quarks and antiquarks. Applying eq. (2), this gives a prediction

$$d\langle \delta Q^2 \rangle_{\text{q}}/dy = 286 \pm 23. \quad (6)$$

The measured value of the hadronic net charge fluctuation is [8]

$$\begin{aligned} d\langle \delta Q^2 \rangle_{\text{had}}/dy &= \frac{1}{4} D \times dN_{\text{ch}}/dy \\ &= \frac{1}{4} \times (2.8 \pm 0.05) \times (526 \pm 2 \pm 36) \\ &= 368 \pm 33. \end{aligned} \quad (7)$$

We note that the errors in eqs. (6) and (7) are strongly correlated because they derive, in part, from the same uncertainty in the measured value of the charged particle multiplicity. Clearly, the net charge fluctuations resulting from the recombination of quarks derived in this way can explain only about 80% of the observed fluctuations.

If, instead, we had included only the ground state nonet mesons and octet and decuplet baryons at chemical freezeout, the inferred number of hadrons at  $T_c$  would have been larger,  $dN_{\text{had}}/dy = 635 \pm 43$ , because fewer decays contribute to the final multiplicity. The number of recombining quarks would be accordingly larger, about 1377, yielding the increased prediction

$$d\langle \delta Q^2 \rangle_{\text{q}}/dy = 345 \pm 29, \quad (8)$$

which is close to the observed value eq. (7).

A third way of estimating the number of constituent quarks at the moment of recombination is to start from the value  $dS/dy \approx 4450$  derived by Pratt and Pal and use the calculated entropy per hadron ( $S/N = 5.15$ ) for a resonance gas at  $T_c$  to obtain an estimate for the number of hadrons at freezeout:  $dN_{\text{had}}/dy = 864 \pm 78$ . This value translates into an estimate for the net charge fluctuations from quark recombination of

$$d\langle \delta Q^2 \rangle_{\text{q}}/dy = 487 \pm 39, \quad (9)$$

which lies significantly above the observed value. Considering the systematic uncertainties inherent in these estimates, we may conclude that the observed net charge

fluctuations in Au+Au collisions at RHIC are compatible with the mechanism of bulk hadronization via recombination of valence quarks in the absence of significant net charge correlations among the quarks. However, a more detailed estimate on the possible production of entropy in the hadronic phase would be desirable to better constrain the analysis. Another source of uncertainty in our analysis is the possibility of the net-charge fluctuations increasing modestly in the hadronic phase due to diffusion [3].

We now discuss a modified variant of the recombination process. Recently, quenched lattice QCD calculations have shown evidence for the existence of mesonic bound state correlations even above the critical temperature [28, 29, 30, 31]. Brown *et al.* argued within an effective field theory that bound states of charmed quark mesons, light quark mesons and gluons exist above  $T_c$  [32]. These findings suggest that  $qq$  and  $q\bar{q}$  pairs may participate in hadronization mechanism as “elementary” constituents, just like individual quarks and antiquarks. In order to explore such a scenario, we modified eq. (2) as follows:

$$\langle \delta Q^2 \rangle = \sum_i (q_i)^2 \langle n_i \rangle + \sum_{ij} (q_i + q_j)^2 \langle n_{ij} \rangle + \sum_{ij} (q_i - q_j)^2 \langle \bar{n}_{ij} \rangle, \quad (10)$$

where  $n_{ij}$  and  $\bar{n}_{ij}$  are the number of  $qq$  and  $q\bar{q}$  pairs, respectively. For simplicity, we assume that the average number of  $qq$  ( $q\bar{q}$ ) pairs is proportional to the products of the individual quark numbers:  $\langle n_{ij} \rangle = \alpha N_i N_j$ ;  $\langle \bar{n}_{ij} \rangle = \beta N_i N_j$ , where  $\alpha$  and  $\beta$  are the relative pairing weights. We have again neglected the correlation terms.

The first term in eq. (11) yields eq. (5). The second term, which denotes the contribution from diquarks, is given by

$$\begin{aligned} & \sum_{ij} (q_i + q_j)^2 \langle n_{ij} \rangle \\ &= \frac{16}{9} \alpha N_u N_u + \frac{4}{9} \alpha (N_d N_d + N_s N_s + N_d N_s) \\ &+ \frac{1}{9} \alpha (N_u N_d + N_u N_s) + (q \rightarrow \bar{q}), \end{aligned} \quad (11)$$

while the third term, denoting the contribution from quark-antiquark pairs, is:

$$\begin{aligned} & \sum_{ij} (q_i - q_j)^2 \langle \bar{n}_{ij} \rangle \\ &= \beta (N_d N_{\bar{u}} + N_s N_{\bar{u}} + N_u N_{\bar{d}} + N_u N_{\bar{s}}). \end{aligned} \quad (12)$$

We can now constrain the parameters  $\alpha$  and  $\beta$  using experimental value of  $\langle \delta Q^2 \rangle$  for the two cases discussed above, counting only ground state hadrons or all known resonances at chemical freezeout. The total number of quarks and antiquarks on the right-hand side of eq. (11)

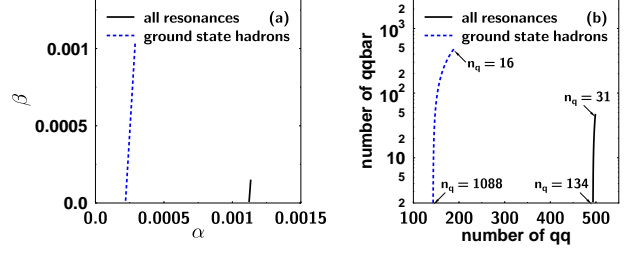


FIG. 1: (a) Relation between the weight of the contributions from  $qq$  and  $q\bar{q}$  pairs in the recombination process. The solid (dashed) line corresponds to a fixed total number of quarks and antiquarks of 1125 (1377). (b) Relation between the number of individual quarks (antiquarks) and the number of diquarks or  $q\bar{q}$  pairs participating in the recombination process.  $n_q$  is the number of quarks and antiquarks contributing to the first term of eq. (11).

is constrained to be the same as that obtained from the statistical model.

Figure 1(a) shows the relation between the weights of  $qq$  and  $q\bar{q}$  pairs. This calculation is done in the simplest case ( $N_u = N_{\bar{u}} = N_d = N_{\bar{d}}$ ,  $N_s = N_{\bar{s}}$ ). The important point is the existence of the region where both  $\alpha$  and  $\beta$  are positive, which confirms the possibility of a contribution from  $qq$  and  $q\bar{q}$  pairs in the hadronization mechanism. We observe a similar tendency in both cases, counting ground state hadrons or all resonances. Diquark pairs are more favored than  $q\bar{q}$  pairs in the sense that a solution with  $\beta = 0$  is possible, but one with  $\alpha = 0$  is not. In fact, the value of  $\beta$  is not well constrained by the charge fluctuations, because the difference between the charge of  $qq$  and  $q\bar{q}$  in eqs. (11) and (12). For example, in the simplest case,  $\sum_{ij} (q_i + q_j)^2 \langle n_{ij} \rangle \sim \frac{42}{9} \alpha N_u^2$  and  $\sum_{ij} (q_i - q_j)^2 \langle \bar{n}_{ij} \rangle \sim 2\beta N_u^2$ , which implies that  $qq$  pairs are favored by a factor of about 2. Perturbative QCD suggests that the  $q\bar{q}$  channel is more attractive than the  $qq$  channel, implying  $\alpha < \beta$  in eq. (11). In Fig. 1(a) the lower part of the dashed line and the whole solid line are forbidden if this condition is imposed. However, since the lattice results indicate that hadronization occurs via strong interactions between plasma quasi-particles, it is not clear that this perturbative argument is applicable.

In order to clarify the relative numbers of diquarks, quark-antiquark pairs, and individual (anti-)quarks participating in the recombination process, we plot the relation among  $\sum_i N_i$  for quarks and antiquarks,  $\sum_{ij} N_{ij}$  for diquarks, and  $\sum_{ij} \bar{N}_{ij}$  for quark-antiquark pairs in Fig. 1(b). In the full resonance gas scenario, for example, we have  $\sum_i N_i = 134$ ,  $\sum_{ij} N_{ij} = 493$ , and  $\sum_{ij} \bar{N}_{ij} = 2$ , showing that  $qq$  clustering dominates. The numbers of quarks and antiquarks decrease linearly as those of diquarks and quark-antiquark pairs increase along the solid and dashed lines, respectively. In the ground state hadrons only scenario, we find a region where recomb-

nation from individual quarks and antiquarks is dominant. On the other hand, in the full resonance gas scenario, hadrons are predominantly created from diquark or quark-antiquark clusters, which is difficult to reconcile with the elliptic flow data from RHIC [20, 21], since that data strongly suggests a constituent quark counting rule [14, 15, 16, 18]. If we demand that the weight of individual quarks and antiquarks in the recombination process should be so large that the quark number scaling approximately survives, the full resonance gas scenario is disfavored.

In summary, we have investigated charged particle fluctuations at RHIC in the framework of the parton recombination model of hadronization and find that within the present systematic uncertainties parton recombination is compatible with the measured charged particle fluctuations. We found that the behavior of the entropy density for an interacting deconfined system close to  $T_c$  and the entropy per particle for the massive resonance gas support the recombination picture. Finally, we have investigated the possibility of bound state correlations above  $T_c$  and find them consistent with the parton recombination approach as well, albeit constrained by the valence quark number scaling observed in the data.

The authors thank T. Renk for critical discussions and for communicating the results of statistical model calculations. They also thank K. Kanaya for the original numerical data for Tables I and II. This work was supported in part by RIKEN, Brookhaven National Laboratory, the U. S. Department of Energy (grants DE-AC02-98CH10886, DE-FG02-96ER40945 and DE-FG02-03ER41239), the Japanese Ministry of Education (grant-in-aid 14540255), and the National Science Foundation (grant NSF-INT-03-35392).

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